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# Quark deconfinement and the duration of short Gamma Ray Bursts

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We propose a model for short duration gamma-ray bursts (sGRBs) based on the formation of a quark star after the merger of two neutron stars. We assume that the sGRB central engine is a proto-magnetar, which has been previously invoked to explain the plateau-like X-ray emission observed following both long and short GRBs. Here, we show that: i) a few milliseconds after the merger it is possible to form a stable and massive star made in part of quarks; ii) during the early cooling phase of the incompletely formed quark star, the flux of baryons ablated from the surface by neutrinos is large and it does not allow the outflow to achieve a bulk Lorentz factor high enough to produce a GRB; iii) after the quark burning front reaches the stellar surface, baryon ablation ceases and the jet becomes too baryon poor to produce a GRB; iv) however, between these two phases a GRB can be produced over the finite timescale required for the baryon pollution to cease; a characteristic timescale of the order of $\sim 0.1$ s naturally results from the time the conversion front needs to cover the distance between the rotational pole and the latitude of the last closed magnetic field line; v) we predict a correlation between the luminosity of the sGRB and its duration, consistent with the data; vi) our model also predicts a delay of the order of ten seconds between the time of the merger event and the sGRB, allowing for the possibility of precursor emission and implying that the jet will encounter the dense cocoon formed immediately after the merger.

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Both long duration (lGRBs) and short duration Gamma Ray Bursts (sGRBs) start with a violent "prompt" emission phase, which generally lasts a few tens of seconds in the case of lGRBs and a few tenths of a second in sGRBs. The prompt emission is in many cases followed by some form of prolonged engine activity, commonly referred to as the "Quasi-Plateau" (QP) in the case of lGRBs and "Extended Emission" (EE) in the case of sGRBs [1]. Beyond similarities in their light curve behavior, sGRBs and lGRBs show remarkably similar spectral properties [2]. This led to the suggestion that a similar central engine is acting in both classes of GRBs, a sGRB being similar to a lGRB cut after $0.3(1+z)$ s [3].

The progenitors of lGRBs and sGRBs, on the other hand, are believed to be quite different: the collapse of a massive star for long bursts [4] and the merger of two neutron stars (or of a neutron star and a black hole) for the short bursts [5]. In their original forms, both models postulated a hyper-accreting black hole as the source of the relativistic outflow powering the GRB. However, following the discovery of the prolonged emission, a new model for the engine has grown in popularity, based on the relativistic wind of a newly formed, rapidly rotating proto-magnetar [6, 7]. The model was initially proposed to explain the structure of lGRBs, but more recently it has been adapted to interpret also sGRBs [8–10] [43].

GRB prompt emission results from dissipation within a relativistic jet composed of electron-positron pairs, photons and a small (but non-negligible) fraction of baryons [11]. The latter plays a fundamental role by setting the bulk Lorentz factor $\Gamma$ of the jet, with values of $\Gamma \sim 10^2 - 10^3$ required to match the observational data in most jet emission models [12]. In the case of a proto-magnetar, the requisite baryon loading is set naturally by the rate of mass ablation from the surface by neutrino heating [7]. The duration of the initial prompt phase is therefore closely connected with the cooling time of the proto-neutron star, which indeed typically lasts tens of seconds or longer. The subsequent quasi-plateau is also powered by the still rapidly rotating magnetar, but the emission properties are likely to change once the wind reaches a high magnetization (pulsar-like) state after baryon loading ceases. Model fits of QP light curve to the dipole spin-down luminosity successfully describe the data [13, 14]. The same modeling applied to the EE of sGRBs [10] generally finds acceptable fits for similar values of the initial rotation period $P \sim$ few milliseconds, but the required dipole magnetic field strength $B$ is roughly an order of magnitude larger than for lGRBs.

If the magnetar model is correct, a crucial question naturally arises: what is the origin of the prompt emission for sGRBs? If broadly similar values of $P$ and $B$ are needed to describe the QP and the EE, then why is sGRB prompt emission typically two orders of magnitude shorter than in lGRBs? The cleaner environment for the jet to escape, and the larger peak temperature of the proto-magnetar (reaching $\approx 50$ MeV [15]) in NS mergers compared to core collapse, would on the contrary suggest that the sGRB prompt emission should last even longer than that of lGRBs!

In this Letter, we propose that due to the large mass of the proto-magnetar formed after a neutron star merger its nature is that of a quark star and not of a neutron star [16, 17] following the "two-families" scenario of Ref.[17–

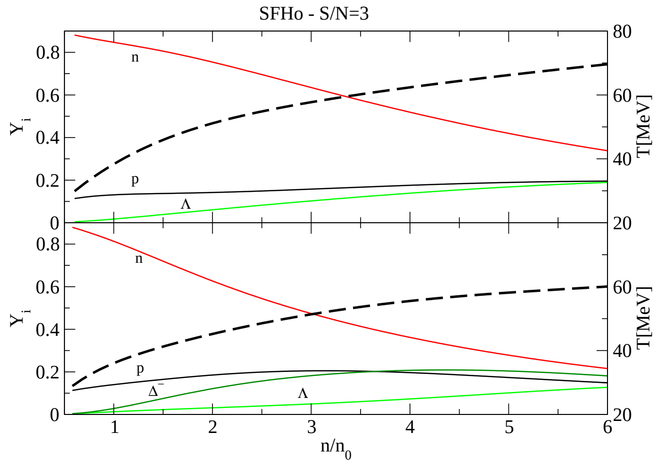


FIG. 1: Fractions of neutrons, protons, Lambda (and $\Delta$-resonances in the lower panel) as a function of the density (left scale). Temperature (right scale). They are computed for matter having entropy per baryon of $S/N = 3$.

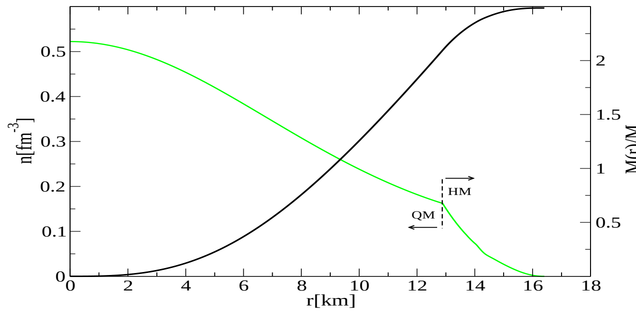


FIG. 2: Density profile (green line) and mass enclosed (black line) of the "hybrid" star formed after the rapid combustion as a function of the distance from the center.

19] in which light compact stars are made of hadrons while the most massive ones are quark stars. Quark stars are self-bound objects, such that neutrinos with energies of a few tens MeV are not energetic enough to ablate material from the surface of the star [20, 21]. Therefore, after the complete transformation of the newly formed compact star into a quark star, no baryonic material can be ablated from its surface and the prompt emission has rapidly to terminate. We associate this brief phase of cessation of the baryonic pollution with the duration of the prompt emission in sGRBs.

Below, we will show that: 1) the formation of quark matter can take place within a few milliseconds after the merger, stabilizing the massive compact star; 2) the rate of baryon ablation from the surface during the formation of the quark star (until its conversation is complete) is too high to produce prompt GRB emission; 3) the duration of the prompt emission in sGRBs can therefore be linked to the switch-off of the baryonic emission, a process which we will show is indeed expected to last a few tenths of a second. In this way the prompt phase of sGRBs will look like that of lGRBs but cut at the moment of the switch-off, satisfying the analysis of Ref. [3].

We start by showing that, in the newly-formed compact star created by the merger, the conditions for initiating quark deconfinement are fulfilled. In Fig. 1 we display the composition of matter at beta-equilibrium and with an entropy-per-baryon $S/N = 3$. This corresponds to a temperature in the center of the merger remnant of about 50 MeV, similar to what found by the simulations of Ref.[15]. We have employed the EoS SFHo obtained in [22] which satisfies all existing constraints below nuclear matter saturation density $n_0$ and we have taken into account the possible formation of $\Delta$-resonances [23]. We also show in Fig.1 the EoS excluding $\Delta$'s to prove that the mechanism we are describing does not depend on the details of the hadronic EoS. Importantly, note that hyperons are present already at densities of the order of $n_0$ (in agreement with Ref.[15]) due to the high temperature of the system. Bubbles of deconfined quark matter (here described by the EoS of Ref.[24]) will start appearing throughout the central region of the star on the time-scale of strong interaction (the temperature is large enough that thermal nucleation can take place [25]) and will rapidly expand following the scheme of Ref.[26]. The central region will deconfine on a time-scale of $\sim 3 - 4$ ms [27, 28] since in this initial phase the burning front is strongly accelerated by hydrodynamical instabilities.

This phase of rapid burning halts at a depth of a few kilometers below the stellar surface, leaving the external layers unburnt and producing in a few ms an intermediate configuration which is mechanically stable, but not yet chemically equilibrated. In Fig. 2 we show the profile of this configuration, as mass-enclosed vs radius. Numerical simulations of the merger process (e.g., [15]) show that, if the mass is not too large, the merger remnant can survive longer than 10 ms (due to its rapid differential rotation) before collapsing into a black-hole. For the EoS we are using, a direct collapse will not occur for the common case of the merger of two 1.3 $M_\odot$ stars, even neglecting the additional stabilizing effect due to the stiffening of the EoS [29–31] [44].

After the conversion of the inner region to quark matter, what follows is a process of much slower burning which, being no longer accelerated by hydrodynamical instabilities, typically lasts a few tens of seconds [26] [45]. The entire star has converted to quark matter only after this slower burning front has reached the remnant surface. We will show that during this phase, no relativistic outflow - and hence no prompt GRB emission - is expected from the merger remnant, similarly to what happens in lGRBs. This is because in proto-magnetar models the maximum achievable Lorentz factor of the flow is given by $\Gamma_{\max} \sim \dot{E}/\dot{M}c^2$, where $\dot{E} \sim B^2 R^6 (2\pi/P)^4/3c^3$ is the magnetic Poynting flux, $R$ is the stellar radius, and $\dot{M}$ is the mass loss rate due to neutrino heating [7]. As long as the star maintains an external layer of baryons, nucleons can be ablated from its surface by thermal neu-

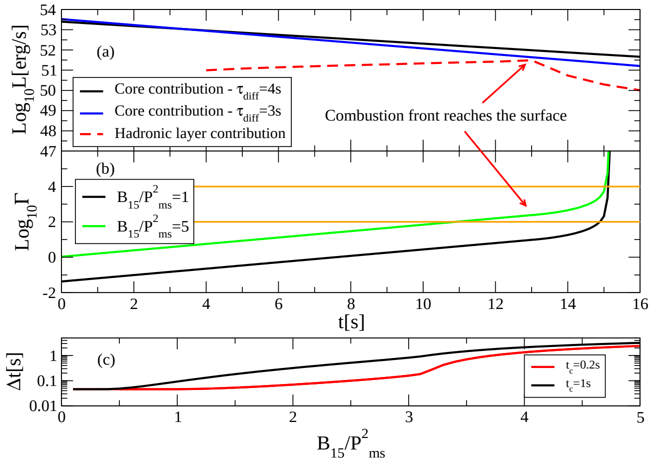


FIG. 3: *Panel (a)*: total neutrino luminosity. Solid lines correspond to the luminosity associated with the rapid burning of the central area (and two different values for the diffusion time). Dashed line the neutrino luminosity of the slow combustion of the external layer of the star. *Panel (b)*: Maximum bulk Lorentz factor of the magnetar jet, $\Gamma_{\max}$, as a function of time, shown for two values of $B/P^2$, where $B$ is the magnetic dipole and $P$ the rotation period. The two horizontal lines bracket the range of values of $\Gamma_{\max}$ required to produce GRB prompt emission according to conventional models. Here and in panel (a) the arrows indicate the time $t_0 \sim$13 s at which the conversion of the remnant into a quark star is completed. *Panel (c)*: duration of the prompt emission of the sGRB as a function of $B/P^2$, shown for two values of the time needed for baryon cessation $t_c$ (see text).

trinos with energies of a few MeV.

The evolution of $\dot{M}$ is quite complicated. During the first tenth of a second it reaches values as large as $\dot{M} \sim 10^{-3} M_\odot s^{-1}$ [32]. In the following few seconds, the baryon flow is associated with the generation of protons via $\beta$-decay in the cooling process. In this way the remnant atmosphere becomes progressively more proton rich, similar to the evolution of a proto-neutron star after a supernova explosion. In our simple analysis we borrow from the existing literature the result that $\dot{M}$ remains very large for a few seconds [33] and we assume that it can be approximated better and better with the formula used in the case of a proto-neutron star after a supernova explosion. In that case $\dot{M}$ is approximately given by [34]:

$$\dot{M} \sim 1.2\times10^{-9} C^{5/3} L^{5/3}_{\overline{\nu}_e,51} \epsilon^{10/3}_{\overline{\nu}_e,\mathrm{MeV}} M^{-2}_{1.4} R^{5/3}_6 M_\odot s^{-1}\,, \quad (1)$$

where $L_{\overline{\nu}_e,51}$ is the electron anti-neutrino luminosity in units of $10^{51}$ erg, $\epsilon_{\overline{\nu}_e,\mathrm{MeV}}$ is their energy in MeV, $M_{1.4}$ is the neutron star mass in units of 1.4 $M_\odot$, $R_6$ is the radius of the star in units of $10^6$ cm, and $C \sim 2$ is a correction factor to account for additional channels of neutrino heating [34]. The energy of neutrinos from the merger remnant is typically $\approx 10$ MeV [35].

The crucial ingredient in the calculation of $\dot{M}$, and hence $\Gamma_{\max}$, is the neutrino luminosity. This has been evaluated in [28], accounting only for the heat deposited during the rapid burning of the central region, while [26] also evaluates the emission associated with the prolonged burning of the external layer. The contributions to the neutrino luminosity from the initial phase of prompt burning in the core, $L_\nu^c$, can be approximated in a simple way by introducing the neutrino diffusion time $\tau_{\mathrm{diff}}$. Following Ref. [28]:

$$L_\nu^c \sim Q/\tau_{\mathrm{diff}}\, \mathrm{e}^{-t/\tau_{\mathrm{diff}}}\,, \quad (2)$$

where $Q \sim (2-3)\times10^{53}$ erg is the total heat deposited by quark deconfinement during the rapid burning phase and $\tau \sim 2(3)$s for a star of mass 1.4(1.8) $M_\odot$, respectively. We employ a similar formula in the merger case, but accounting for the larger amount of heat deposited, $Q \sim 10^{54}$ erg (also due to the gravitational potential energy before the merger and in part to the use of a different equation of state), and $\tau_{\mathrm{diff}} \sim 3-4$ s, the latter estimated following Ref.[35] (their eq. 6).

Fig. 3 shows that, while the quark star is still forming, the neutrino luminosity is very large and it corresponds to a mass loss rate of $\approx 10^{-4} M_\odot s^{-1}$. Therefore the Lorentz factor does not reach high enough values to produce the GRB prompt emission. This stage mirrors the early evolution of the proto-magnetar in lGRB, where no relativistic jet is created during the first $\sim 10$ s after core bounce due to the high baryon load. In the case of lGRBs, after that phase the baryon load slowly reduces and a GRB lasting a few tens seconds is produced. Notice that in the case of lGRB, the mass of the proto-magnetar and its initial temperature are significantly smaller and quark deconfinement need not to take place. By contrast, in the merger case, the quark conversion is unavoidable and when the front reaches the stellar surface baryonic ablation ceases. To zeroth order, therefore, the prompt emission from the rotating magnetized merger remnant is suppressed at all epochs: the mass loss rate is too large prior to quark conversion, or too low after the conversion. In neither case can a prolonged relativistic outflow of the appropriate Lorentz factor form. In this zero-order approximation, the maximum Lorentz factor $\Gamma_{\max}$ jumps from values of the order of unity to, virtually, infinity.

Such a sudden jump in the outflow's Lorentz factor is clearly not physical: what is missing is a description of the period over which the most external layer of the star is converted into quarks. Even if baryon loading were to cease abruptly, a minimum time would be required to clear the jet of baryons, which we estimate to be $t_{\mathrm{d}} \sim 0.01$ s as the dynamical timescale near the base of the wind (Ref. [36], Fig. 9). However, there is a potentially more important effect that delays the time for baryon cessation. Since the star is rapidly rotating near centrifugal break-up, its shape is deformed into an ellipsoid with an equatorial radius $R_{\mathrm{eq}}$ larger than its polar radius $R_{\mathrm{p}}$. For a soft EoS, such as that we employ for the hadronic phase, we expect $R_{\mathrm{eq}}/R_{\mathrm{p}} \sim 1.2-1.4$ for a rotation rate of $\sim 1$ kHz [37]. Using the results of Ref.[26], we estimate that the burning front will reach the pole and the equator at times $t_{\rm p}$ and $t_{\rm eq} \approx (1.2-1.4)t_{\rm p}$, respectively. Since $t_p \sim (10-20)$ s, the quark conversion of the star will move from pole to equator over a characteristic timescale of $\Delta t \sim t_{\rm eq} - t_{\rm p} \sim$ a few seconds.

However, in fact baryon mass loss from the strongly magnetized remnant is confined to a relatively narrow range of latitudes near the axis of the magnetic dipole, which is likely to be aligned with the rotation axis. The latitudinal extent of this 'open zone' of the magnetosphere is given by $\theta_{\rm open} \approx (R/2R_{\rm L}) \approx 0.1R_6(P/2{\rm ms})^{-1}$, where $R_{\rm L} = 2\pi Pc$ is the light cylinder radius. Thus, for typical values of $P \sim 2$ ms, we expect the true timescale for baryon cessation to be given by $t_c \approx \theta_{\rm open}(\Delta t \sim t_{\rm eq} - t_{\rm p}) \sim$ a few 0.1 s, comparable to the duration of sGRBs.

Fig. 3 shows our results for the duration of the sGRB prompt emission, which we indeed find to be of the right order of magnitude. sGRBs of the longest duration may start even during the final seconds of the baryon emission, before deconfinement reaches the surface (as occurs if $\dot{E}$ is very large), while the shortest duration are instead regulated by $t_{\rm d}$. Interestingly, we predict a strong correlation between the sGRB duration and its luminosity (which is $\propto B^2/P^4$), which is indeed observed [38].

Finally, in our model it is possible to have precursor signals: since the inner engine is already active during the first ten seconds, some high energy emission can originate from the jet before the main event starts. Precursors have indeed been observed from sGRBs [39].


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[43] Models for sGRBs based on the formation of a black hole are still actively discussed, see e.g. Refs.[40, 41] and the criticism raised in [42].
[44] The interesting scenario, in which at least one of the two stars is already a quark star, will be discussed in a future paper. The presence of stiff quark matter already inside the merger constituents will likely result in the merger remnant remaining stable up to the maximum mass allowed for a non-rotating quark star [16, 17].
[45] Here we use for $a_0$ of Ref.[26] the central value $a_0 = 0.5$.